STRUCTURAL EFFECTS OF AERODYNAMIC HEATING

Part I - The Nature of Aerodynamic Heating Effects

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When an airplane or missile flies through the atmosphere at supersonic speed, it compresses and heats the air adjacent to its surface. A portion of the heat so generated is continually transferred into the aircraft structure, and if the flight is sustained long enough, the structure can be brought to a high temperature by this aerodynamic heating action. This curve (C-35919) shows the ultimate temperatures that could be reached by an aircraft structure after a sustained flight in the stratosphere at these Mach numbers. For example, a sustained flight in the stratosphere at three times the speed of sound would heat the aircraft structure to about 600° F.

The structural design of supersonic aircraft, even without consideration of aerodynamic heating, is a challenging task by virtue of the necessity for thin wings and slender bodies that are stiff as well as strong; the effects of aerodynamic heating, as we shall see, may profoundly aggravate the already difficult design problems involved.

It may be of interest to note, in connection with this chart, the speeds that have been achieved by research aircraft in recent years. Thus, the D-558-1 has flown at Mach 0.9; the X-1 at Mach 1.5; the D-558-2 at Mach 2.0; and the X-1A has come close to Mach 2.5. If we note the successively higher temperatures associated with sustained flight at these Mach numbers, it becomes clear that aerodynamic heating of piloted aircraft is certainly more than an academic problem at the present time.

I should mention that the flight of the X-1A near Mach 2.5 lasted only a matter of seconds; consequently, it did not have time to heat up very much. However, if the flight had lasted for only several minutes, the temperature of the structure would have approached 400° F.

This next chart (C-35903) illustrates how rapidly maximum temperatures may be achieved in accelerated flight at supersonic speeds. Consider an airplane, cruising in the stratosphere at a speed just below Mach 1.0; it accelerates to Mach 3.0 in this time interval of slightly more than 1 minute. A calculated time history of skin temperature resulting from this maneuver looks like this. As can be seen, the major portion of the temperature rise is achieved in about a minute. It is important to realize that such very high heating rates, as well as the temperatures they produce, can have serious structural consequences.

The major structural effects of high temperature and rapid heating will be shown on this chart (C-35918). (Illuminate part 1 of C-35918.) The primary effects of higher temperatures on structural materials are to reduce their strength and stiffness properties, and to make them subject to creep, that is, a gradual and permanent increase in deformation under constant load. The aircraft designer is faced with the necessity of choosing a structural material that is most efficient for the range of temperatures at which the aircraft is intended to perform. For example, analytical studies have yielded the results shown on this chart (C-35904) for the best material to use in the skin of aircraft structures designed to operate in various Mach number ranges. It appears that aluminum loses its superiority as a plate material above Mach number 2.0; around Mach 3.0, titanium is the most efficient material; for still higher Mach numbers, and their correspondingly higher temperatures, steel is best. However, even with the use of the most efficient material, creep distortions will occur at elevated temperatures, and the possibility of excessive deformation due to creep must be taken into account in the design of the aircraft.

The effects or rapid heating (illuminate part 2 of C-35918) are perhaps equal in importance to those of high temperature. (Extinguish part 1.) When a structure is subjected to rapid heating, the temperature in the structure varies widely from point to point, at least in the initial stages of heating. Such non-uniform temperature distribution gives rise to stresses. These thermal stresses may have serious structural consequences. I will now demonstrate some of the adverse structural effects of thermal stresses produced by rapid heating.

Thermal stresses may attain magnitudes sufficient to cause buckling (illuminate "Buckling," part 3 of C-35918) of the surface of the aircraft. Such buckle formation will be demonstrated with the aid of this heating apparatus (on wall, left center). The apparatus consists of two identical banks of high-intensity quartz tube heat lamps with tungsten filaments. The heaters will be used to apply a rapid rate of heating to this small-scale test specimen which represents the skin and spar structure of an airplane wing. One side of the skin has been painted black to increase the rate of heat absorption. Note that the surface of the specimen is flat. (Insert specimen in heater.) The heating will take place for only a few seconds.

(Heat specimen. Explain that smoke is caused by burning of the black lacquer. Remove specimen and hold it for audience to see.)

As you can see, the skin now contains buckles, caused by the thermal stresses that resulted from the rapid heating to which the surface was subjected. Such buckles, occurring at high supersonic speed, would not only have adverse aerodynamic effects, but could also precipitate destruction of the aircraft. (Extinguish part 3 of C-35918.)

We have just seen how a wing structure, subjected to conditions comparable to those which would be experienced in supersonic flight, was destroyed as a result ofsome of the adverse structural effects of aerodynamic heating which we have been discussing.

Thus far, we have been concerned with problems of aerodynamic heating associated with aircraft that fly in this speed range (point out Mach number range on abscissa of C-35919). In general, it is expected that these will be aircraft which use engines that obtain their oxygen from the earth's atmosphere, or they may be short-range, rocket-propelled missiles.

There are, however, other rocket-propelled missiles which will fly at much higher speeds. These are the long-range missiles of the so-called ballistic type. Ballistic missiles are projected rapidly out of the earth's atmosphere and after their fuel is exhausted they follow the path of a free projectile. This chart (C-35922) shows typical trajectories of three ballistic missiles. The range, or distance, that is traversed by a ballistic missile is directly related to the speed attained by the missile during the relatively short time in which propellant fuel is burned. The speeds associated with ballistic missiles of these ranges (point to abscissa values) are indicated on each of the trajectories. For example, a ballistic missile with a range of 3000 nautical miles would be accelerated to a speed of about Mach 20 in the initial part of its trajectory. As these freely falling missiles plummet toward the earth, they re-enter the earth's atmosphere at extremely high speeds which result in high temperature, as shown on this chart (C-35917). For example, in the speed range from Mach 5 to 10, flight in the atmosphere could produce temperatures ranging from 2000° to almost 8000° F.

This lower speed range (point out shaded area of C-35917) is that which was discussed in connection with the aerodynamic heating problems previously described and demonstrated. These same problems exist, and indeed can be more severe, for short-time flight at these higher speeds. In addition, at these higher Mach numbers associated with the ballistic type missiles sustained flight in the atmosphere will produce temperatures sufficient to melt the various metals shown here. At the temperatures attainable above Mach 10, diamonds vaporize and, indeed, no presently known material could exist in the solid state. Thus, at these higher Mach numbers, the very physical existence of an aircraft structure is threatened by the heat to which it would be subjected.

I wish to emphasize that the serious and complex structural problems which we have been discussing occur at temperatures well below these which cause the melting of metals. However, inasmuch as the possibility of melting does exist, for example, at the nose of a missile if the time of flight in the atmosphere is long enough, a test was conducted for the purpose of observing the nature of such melting action. A model of a missile nose was made of a low-melting-point alloy and was tested in a wind tunnel at high supersonic speed. We will now show a motion picture of that test. (Movie on.)

Commentary on motion picture of melting missile nose:

Note sharp point on missile model
Pointer indicates temperature in 100° F
Point of missile melts and nose becomes more blunt
Melted nose is approximately hemispherical
Melted material flows back and is then carried away in air stream

This concludes the Langley laboratory presentation.

Description of Charts

C-35919. Title: Temperature Attainable in Sustained Flight. Temperature in °F is plotted vs. Mach number to speed of M = 4. On this chart models of D-558-1, X-1, D-558-LL and X-1A are placed.

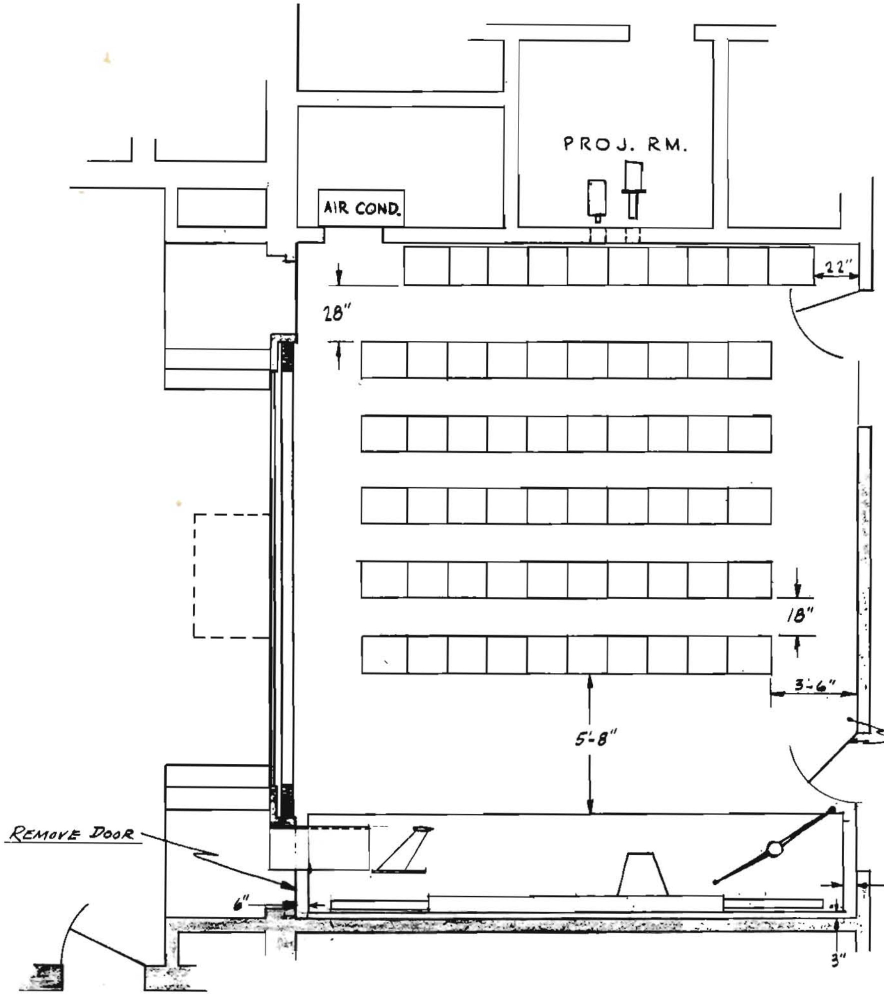
C-35903. Title: Temperature History. On the upper half of the chart a curve of Speed, M, vs. Time, Min., was shown for an airplane accelerating from M = 0.8 to M = 3 in about 1 minute. On the lower chart a temperature-time history for the skin is given for the airplane.

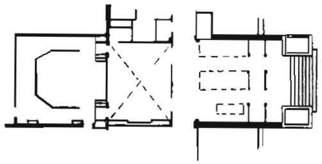
C-35918. This was a backlighted panel with separate lighting circuits for five items of information. Each item was illuminated in correlation with text.

C-35904. Title: Most Efficient Blade Material. On curve of Temperature vs. M, shaded portions were marked to indicate the ranges over which aluminum, titanium, and steel materials would be most efficient for use in the skin of an aircraft.

C-35922. Title: Trajectories of Ballistic Missiles. On a chart of Altitude vs. Range, both in nautical miles, trajectories of missiles with maximum speeds of M = 10, 15, and 20 are given.

C-35917. Title: Temperature Attainable in Sustained Flight. This chart is an extension of C-35919 to a speed of M = 15. On the temperature curve, melting temperatures of several metals are indicated.





1 9 5 4 INSPECTION

EIGHT x SIX FOOT S.S.W.T. OB. ROOM

LEWIS FLIGHT PROPULSION LAB.

SCALE 1/4" = 1'-0"

LANGLEY LAB. STOP

WHH 5/18
JUM 4/18

SEAT WIDTH - 20", PROJECTOR 28 FT.

NACA
C-36017


STRUCTURAL EFFECTS OF AERODYNAMIC HEATING
TEMPERATURE ATTAINABLE IN SUSTAINED FLIGHT
TEMP, °F
1000
800
600
400
200
0
-200
1
2
3
SPEED, M
RAPID THERMAL
HEATING

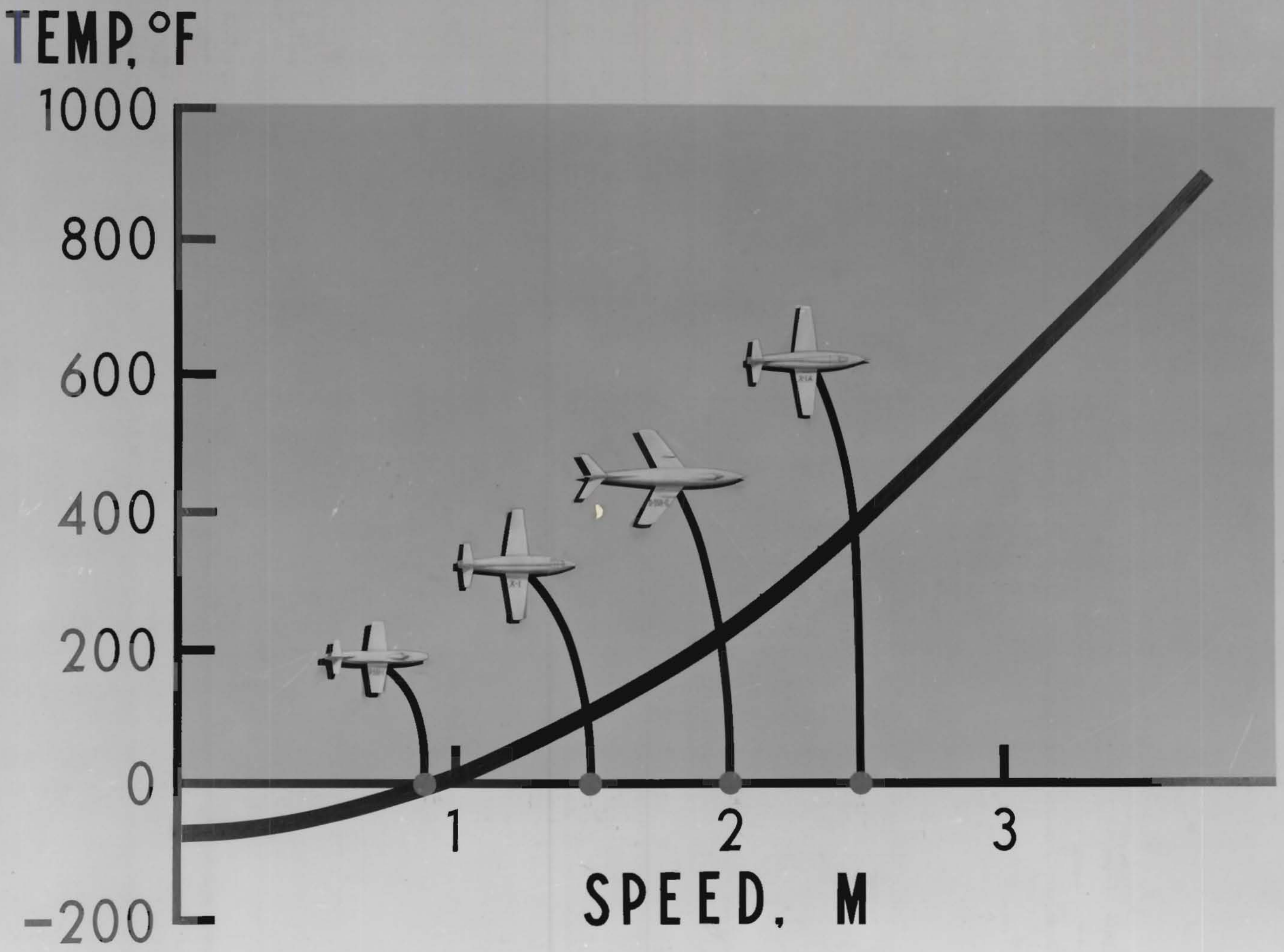
NACA

C-36019


STRUCTURAL EFFECTS OF AERODYNAMIC HEATING
TEMPERATURE ATTAINABLE IN SUSTAINED FLIGHT
TEMP. °F
1000
800
600
400
200
0
-200
1
2
3
SPEED, M
RAPID HEATING
THERMAL STRESSES
BUCKLING

NACA
C-35919

TEMPERATURE ATTAINABLE IN SUSTAINED FLIGHT



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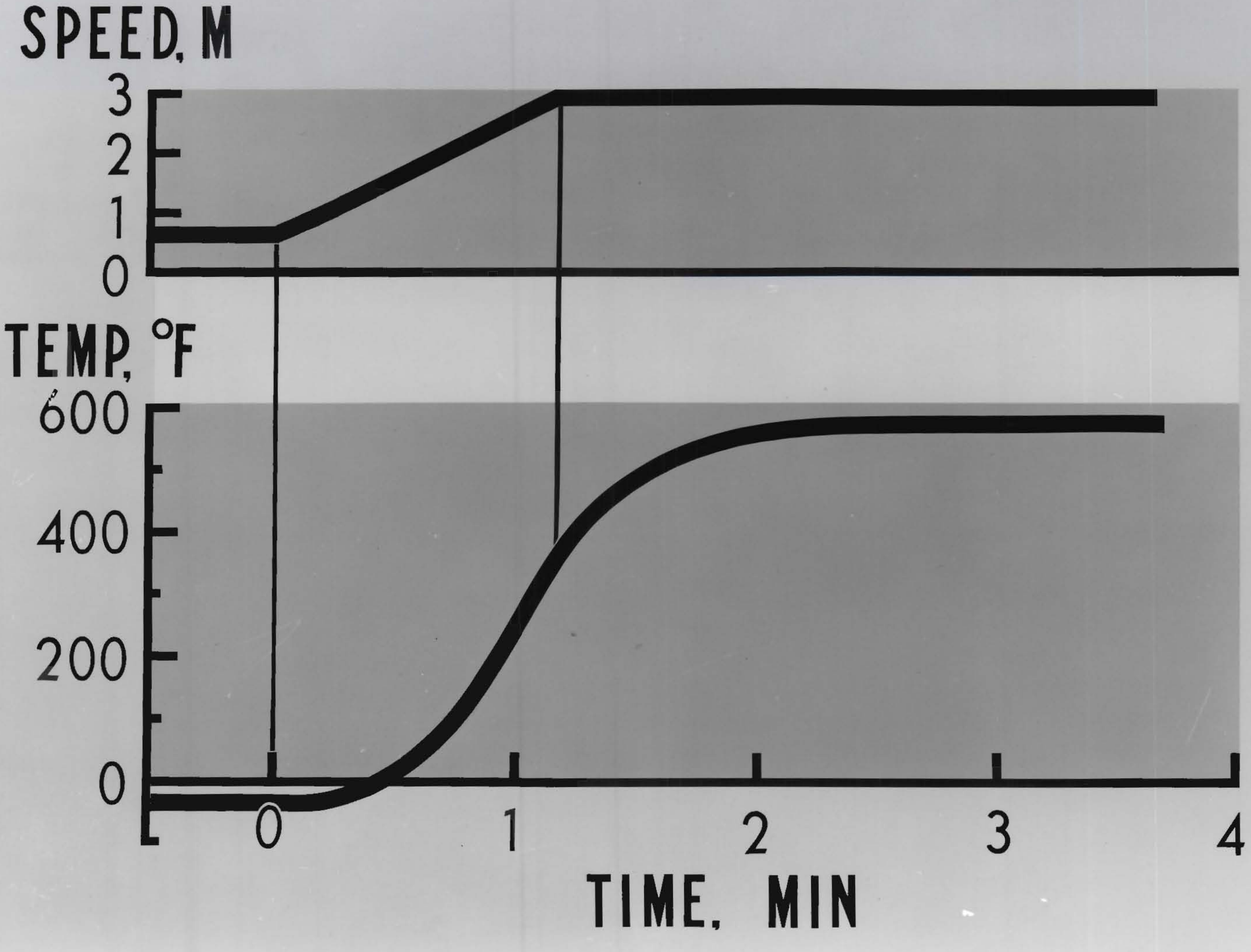
C-35903

TEMPERATURE HISTORY



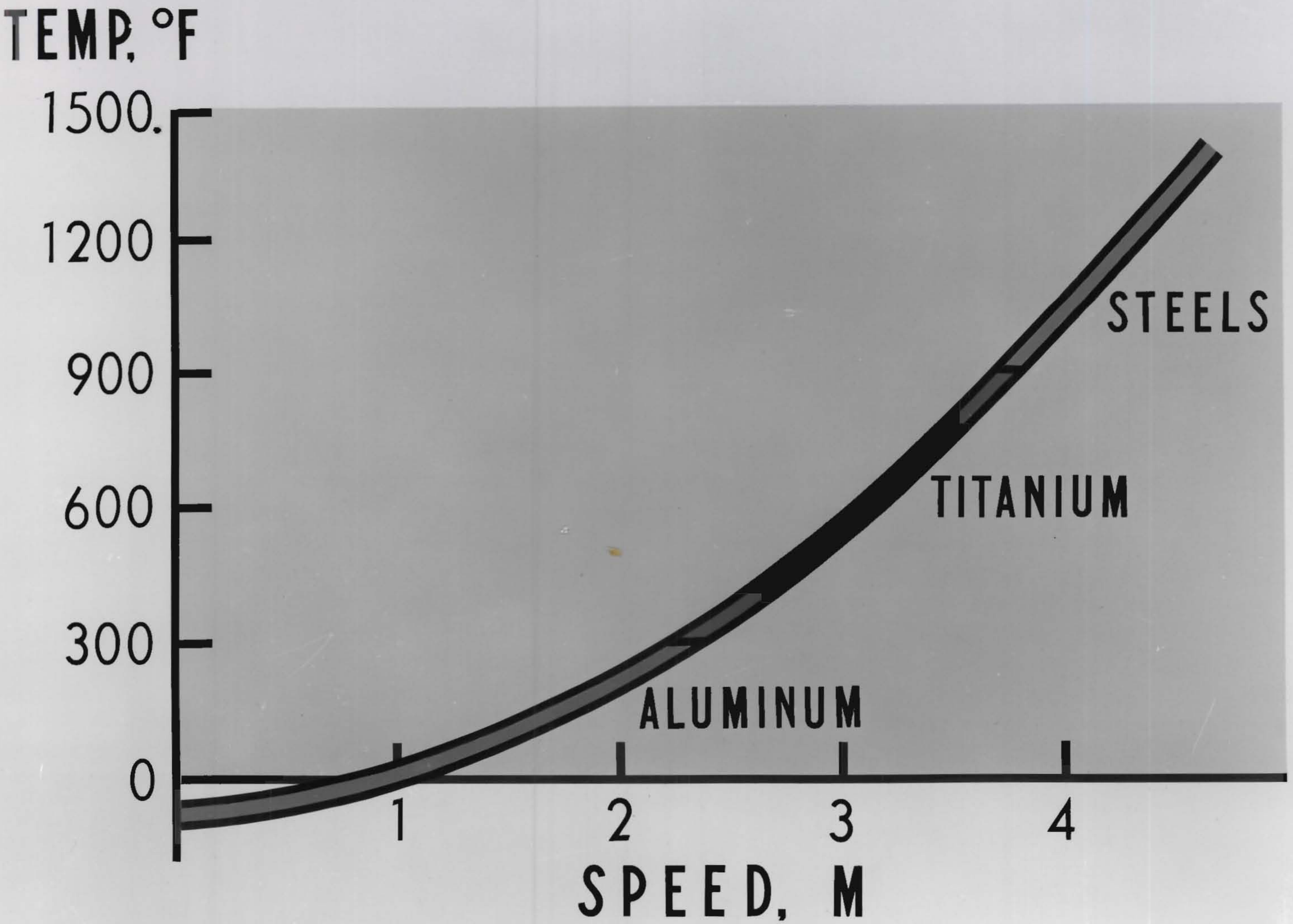
NACA
C-35918

ELEVATED TEMPERATURE →
- a. DETERIORATION OF MATERIAL PROPERTIES
- b. CREEP

RAPID HEATING → THERMAL STRESSES →
- BUCKLING
- REDUCED STIFFNESS
- FLUTTER

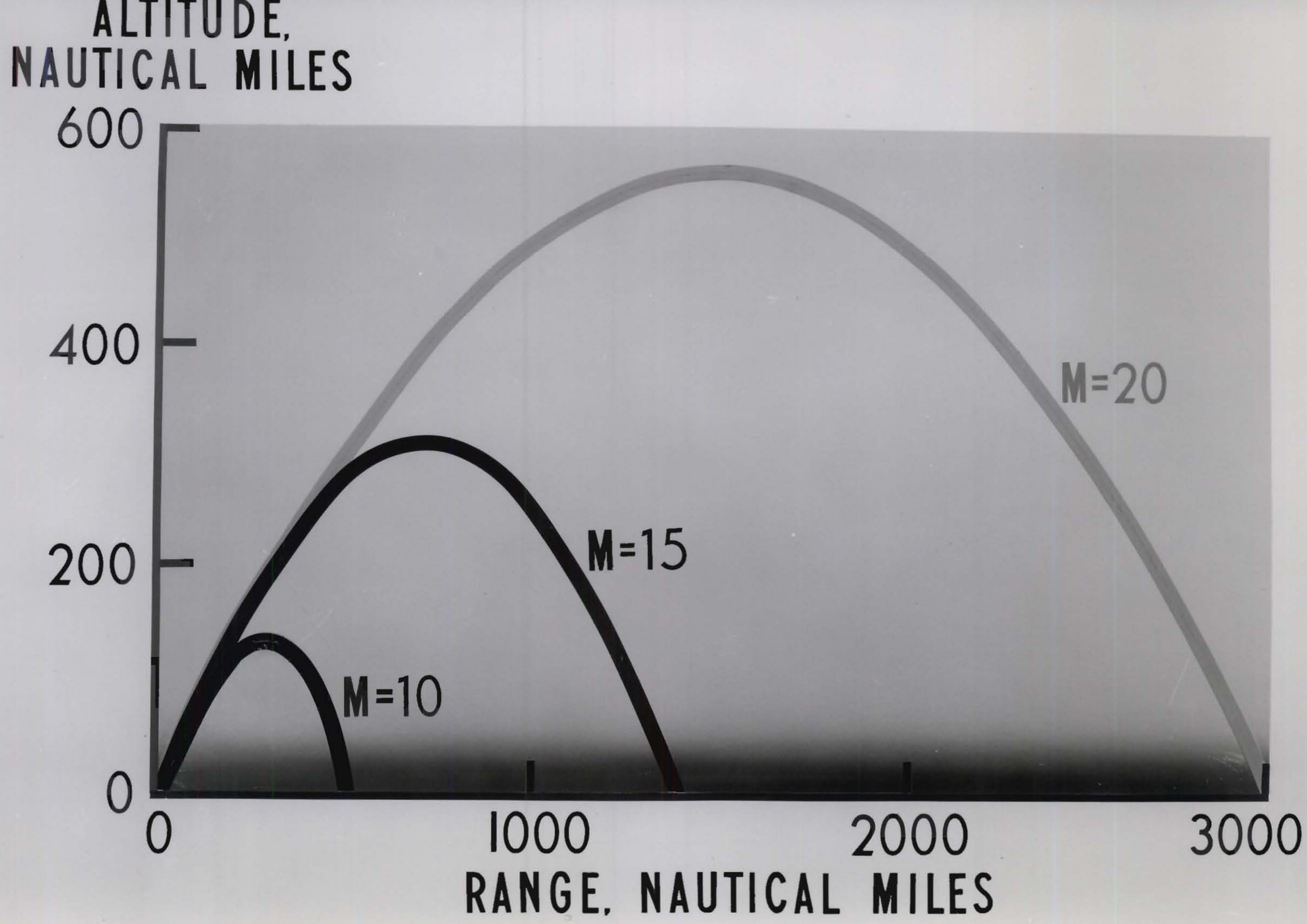
NACA
C-35904

MOST EFFICIENT PLATE MATERIAL



NACA
C-35922

TRAJECTORIES OF BALLISTIC MISSILES



NACA
C-35917

TEMPERATURE ATTAINABLE IN SUSTAINED FLIGHT